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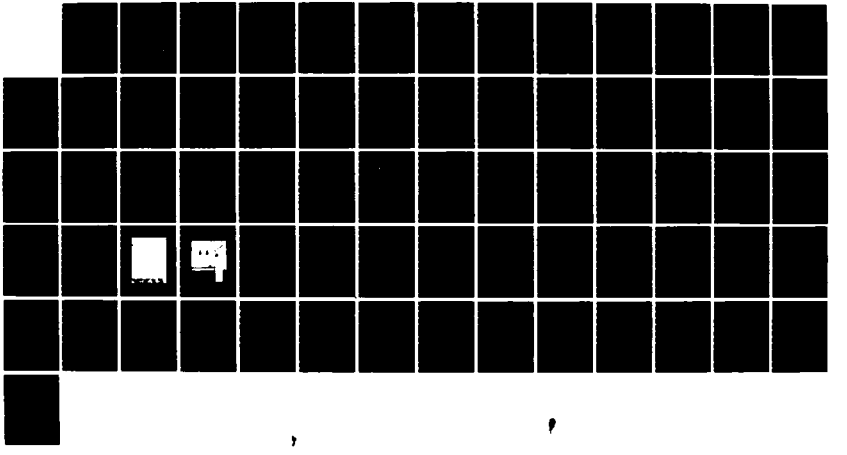

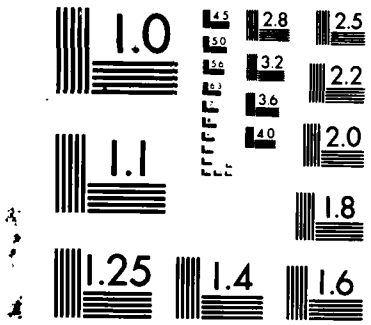

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NAVEODTECHCEN TECHNICAL REPORT TR-278

THE DESIGN OF RADIOGRAPHIC ENHANCEMENT SYSTEMS

SEPTEMBER 1986

FINAL REPORT
(Contract No. N00174-85-C-0055)

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Preliminary specifications and designs are given for two radiographic enhancement systems. The first system is a portable system designed to be carried with EOD teams to enhance the contrast of low-density, low-contrast radiographs made with existing EOD radiographic equipment. The second system contains both image enhancement and improved radiographic equipment and is designed to be carried aboard commercial or military aircraft in an air-transportable pod. Expected production costs and equipment selection are included.

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TABLE OF CONTENTS

ACKNOWLEDGEMENTS 1

SUMMARY 2

INTRODUCTION 3

DESIGN OF SYSTEM I 6

System I Functional Specifications 6

The Computer 8

Video Digitizers 9

Spatial Resolution 11

Gray-Scale Resolution 11

Software Requirements 16

Available Software 16

Video Cameras 18

Logarithmic Amplification of the Video Signal 21

The Light Table 21

Recommended Equipment 22

System I Cost 22

Notes on Packaging 23

DESIGN OF SYSTEM II 24

System IIa Functional Specifications 25

Additional Specifications for System IIb 29

System II Hardware 30

X-Ray Unit 30

Radiographic Films 31

Film Processor 32

Image Intensifier 34

TABLE OF CONTENTS
(Continued)

	Page
Additional Equipment for System IIb	33
Image Digitizer and Recorder	34
Image Processor	35
System IIa Costs	40
System IIb Costs	40
CONCLUSIONS AND RECOMMENDATIONS	41

APPENDIX A

Image Processing Software for the Imaging Technology Frame Grabber	A-1

LIST OF TABLES

Table 1. Video Digitizer	10
Table 2. Smallest Discernible Density Differences	15
Table 3. Measured Camera Resolutions	20

LIST OF FIGURES

Figure 1. Artist's Sketch of the Components of System I	6
Figure 2. Digitized Gray-Scale Values Versus Film Densities for Three Camera Iris Settings	13
Figure 3. Artists's Sketch of the Components of System IIb	26
Figure 4. Artists's Conception of System IIb in the Air Transportable Pod	27
Figure 5. Print of Original Unenhanced Negative Scanned with the P-1700	36
Figure 6. Print of Digitally Enhanced Image in Figure 5 Recorded on the P-1700	37

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Per Mr. Louis Billard, NAVEODTECHCEN

SUMMARY

Explosive ordnance disposal (EOD) teams use radiographic techniques to determine the inner structure of improvised explosive devices (IED's) prior to dearming them. The conditions under which the radiographs are made are often far from ideal. As a consequence, the resulting radiographs may be poorly exposed, making it difficult to accurately ascertain the interior of the device. Because of the type of film and radiographic equipment that EOD teams normally use, most of the poor radiographs are overexposed, giving rise to radiographs which have low film densities as well as having low contrast.

In a previous project[1] conducted for the Naval EOD Technology Center (NAVEODTECHCEN), a variety of ways to enhance the contrast of low-contrast, low-density radiographs were examined. Several recommendations were made at the conclusion of that project. One was that digital contrast enhancement techniques should be used to enhance low-contrast radiographs to allow the EOD teams to discern features even in poor quality radiographs. Another was to improve the radiographic capability of EOD teams by using better films and equipment.

As a result of that project, this project was conducted to design two radiographic systems for NAVEODTECHCEN. The first, called System I, uses existing EOD radiographic techniques and equipment but includes a portable image enhancement system to perform simple types of contrast and image enhancement of poor quality images. System II is a larger, more complex system and includes both a digital enhancement system as well as improved radiographic equipment, all housed in an air-transportable pod. System I is expected to cost around $10,000 in production versions and System II may cost between $150,000 and $400,000 depending on the exact configuration selected. Specific equipment recommendations for each system are included in this report.

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[1] IMAGE ENHANCEMENT OF LOW-CONTRAST, LOW-DENSITY RADIOGRAPHS, April 13, 1984, Contract N00174-83-C-0211

INTRODUCTION

Radiography is a technique commonly used by DoD EOD teams to determine, in as much as possible, the inner workings of improvised explosive devices (IED's) prior to dearming them. Unfortunately, many of these IED's are situated in ways that often prevent the disposal teams from making high quality radiographs. For example, IED's may be located in lockers, next to walls, or may be encased by an unknown thickness of steel or other dense material. As a result, making radiographs which are properly exposed and present a clear picture of the interior features of the IED is difficult.

Current EOD practice is to use a MK-32 150 kV flash X-ray unit with a Polaroid film cassette to make the radiographs. Inside the film cassette is a rare-earth fluorescent intensifying screen to allow the film to respond to the beam of X-rays generated by the flash X-ray unit. In general, this is a good system for EOD teams; it is portable,

easy to use, reliable, and is capable of making good quality radiographs under the right conditions. Moreover, the exposed film can be developed and viewed within several minutes of the exposure. But this system also has several drawbacks. First, the energy of the X-ray beam is fixed and cannot be lowered to enhance small differences in object density as can be done with conventional hot-filament radiographic systems. Second, the film density range of the Polaroid film is limited; as a consequence, the X-ray exposure must be controlled reasonably well to make a good image. And third, the use of intensifying screens, necessary to expose the film with a flash X-ray unit, introduce graininess which reduces the clarity of the image.

Despite these drawbacks, the major problems faced by EOD teams are the inability to properly position the X-ray source and film with respect to the subject (since they are prevented, by the nature of the subject, from moving it) and a lack of knowledge of the interior of the subject which would allow them to correctly set the exposure. And, of course, there is a strong deterrent to not making several radiographs of IED's to obtain the correct exposure, since making the radiographs requires that someone work in close proximity to the explosive device.

There is no solution to these last two difficulties, so ways must be sought instead to improve both the flexibility and capability of the radiographic systems used by EOD teams. One way is to provide a means of enhancing low-contrast (improperly exposed) radiographs in a portable package that can be carried by EOD teams. A second way is to provide EOD teams with better radiographic equipment that will allow more latitude in X-ray energy and exposure levels, yet still make acceptable images.

In a previous research program, various methods by which EOD teams could improve their radiographic capabilities were described. Three recommendations made were:

(1) use digital techniques to enhance contrast of low-contrast, low-density radiographs

(2) use better radiographic films, where possible, with larger available density ranges

(3) use better X-ray machines, where possible, to improve radiographic performance.

Using these recommendations, two enhancement systems have been designed for EOD teams. The first, System I, is built around a portable personal computer with a video digitizer and can enhance the contrast of low-contrast radiographs made using the existing radiographic equipment of EOD teams. System I is comprised of two boxes, each of which can be placed under the seat of an airplane. One box contains the computer and video digitizer, while the other box contains a video camera, light source for backlighting Polaroid radiographs, and miscellaneous hardware. The expected cost of a production version of System I is in the neighborhood of $10,000. In a production lot of 300, the economics of scale would reduce the per unit cost by 10 to 15 percent.

System II contains not only digital image processing/enhancement hardware, but also contains a larger (320 kV) X-ray machine, a variety of radiographic films, an image intensifier, and a film developer. System II, because of the types of equipment used, is not designed to portable but is contained in an air-transportable pod instead. Once transported to the site, the pod opens to form a working area for EOD teams. Because of the larger X-ray machine, System II can be used to penetrate over one inch of steel, as opposed to the nominally 0.25 inches for System I. And because the energy of the X-rays emitted by this machine can be adjusted anywhere from 32 kV to 320 kV, System II can also be used to make high contrast images of less dense objects.

Actually, two versions of System II were designed. The first, System IIa, uses System I as the image processing/enhancement system, while the second, System IIb, uses a far more powerful, and expensive, image digitizer and processor. It is believed that the combination of the improved radiographic capability with the image processing capability of System I (i.e., System IIa) will solve the majority of problems faced by EOD teams -- at less than half the cost of

System IIb. The expected cost of a production version of System IIa is about $150,000, while that for System IIb is nearly $400,000.

This report documents the design considerations for both Systems I and II. Evaluations of hardware and software available for System I and hardware for System II are included.

DESIGN OF SYSTEM I

System I is a portable image processing unit designed primarily to work with radiographs made with the MK-32 flash X-ray unit. System I consists of four basic elements, a portable computer, a high--speed image digitizer, a video camera, and a light table for illuminating the Polaroid radiographs made with the MK-32 unit. The image digitizer fits inside the portable computer, while the video camera is packed into the light table during transport. An artist,s conception of the system in operation is shown in Figure 1.

The functional specifications for System I are listed in the next section. Following that are reviews of the hardware evaluated for System I and the final equipment recommendations and costs.

System I Functional Specifications

Purpose: The primary purpose of Radiographic Enhancement System I is to enhance the contrast of low-contrast and/or low-density radiographs made using current NAVEODTECHCEN radiographic practices.

1. The image source is Polaroid TPX film. Film size is approximately 8.5 x 11 inches (21.6 x 27.9 cm). Image size is approximately 7.5 x 9.5 inches (19.1 x 24.1 cm). Image density range is approximately 0.1 to 3.0.

2. The image sensor shall be a video camera with either a CCD array, newvicon, or vidicon. The latter two are preferred. The resolution of the camera must be greater than 512 optical lines in the horizontal direction and 350 optical lines in the vertical direction.

3. The image source (Polaroid film) shall be illuminated evenly with sufficient light to generate a usable image within the density range specified above.

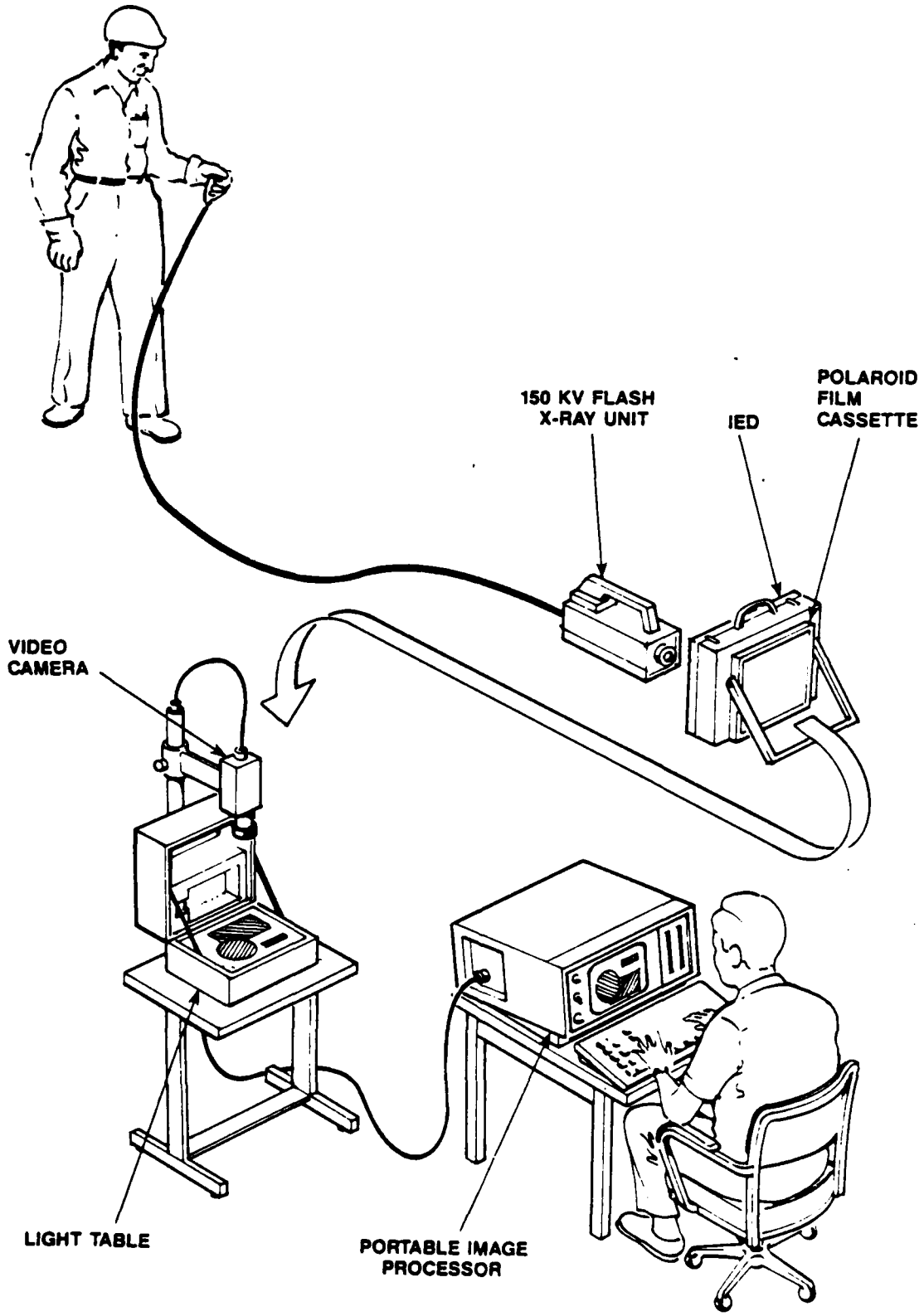

FIGURE 1. ARTIST'S SKETCH OF THE COMPONENTS OF SYSTEM I

4. The image processing system will consist of a portable computer with a video digitizer, integral video monitor, and sufficient memory (512 Kbytes of random access memory is suggested). At a minimum, the portable computer shall contain one 360 Kbyte floppy disk drive and one 10 Mbyte hard disk. The DC power supply and cooling capacity of the personal computer shall be sufficient for the video digitizer selected.

5. The video digitizer shall fit into a slot provided in the computer, and shall be capable of digitizing one full video frame in 1/30 of a second. The resolution of the digitizer shall be greater than or equal to 512 TV lines in the horizontal and 480 TV lines in the vertical direction. The gray scale resolution of the digitizer shall be equal to or greater than one part in 256 (eight bits).

6. The software supplied with the portable computer shall be able to
    a. Digitize an image from the video camera.
    b. Display the digitized image on the integral video monitor.
    c. Provide a means of enhancing the contrast in the digitized image under the control of the operator.
    d. Provide a means of sharpening the digitized image to enhance edges under control of the operator.
    e. Provide a means of performing a time average of the video signal under control of the operator.
    f. Store the original or enhanced image on disk.
    g. Retrieve a previously stored image from disk and display it on the monitor.

7. The image processing software described above shall be easy to use and require minimal training for the operators.

8. The entire image enhancement package shall fit into two packages which are suitable for under-the-seat storage on board a commercial airliner.

The Computer

Several contrast enhancement techniques discussed in the last report[2], such as reproduction of the radiograph with a high-contrast film, could be used to enhance the contrast of EOD radiographs. However, all of the nonelectrical methods are extremely sensitive to slight variations in processing conditions and require several iterations before a good image can be made. Digital contrast enhancement also requires several iterations, but the time required to complete one iteration is very small, so that a large number of trials can be made in less time than one trial of the nonelectrical methods.

For this reason, it was recommended that electrical (more particularly, digital) methods be used to enhance the contrast of low-contrast radiographs. Two possibilities were examined. The first was to use a dedicated image processing system such as the Hughes[3] 794, while the second was to use a general purpose computer with added hardware and software to perform the image processing. The decision to use the second method was prompted by both cost and flexibility. The general purpose computer, since it can be programmed, can perform a variety of image processing functions, though admittedly in a much slower fashion than can be achieved with the dedicated image processing hardware. Moreover, the dedicated systems cost $5,000 to $10,000 more per unit than does a system

---

[2] See 1 above.

[3] Huges Aircraft Company, Image and Display Products, 6155 El Camino Real, Carlsbad, CA 92008

built around a general purpose computer. If this cost is multiplied by the 300 systems expected to be bought for EOD teams, the savings are significant.

All personal computers are built around one of the many families of microprocessors such as the Zilog Z-80, the DEC LSI-11, or the Intel 8088/8086. However, if the constraints of portability and ready availability of add-on hardware and software are imposed, the IBM-PC class of computers, built around the Intel 8088, are the obvious choice. In this class are several varieties of portable computers. The Compaq[4] line is favored because of its reliability and compatibility with the IBM-PC. Of these, the Compaq Plus, with an integral monitor, 10 Mbyte hard disk, and 360 Kbyte floppy disk, is the best choice. The Compaq Plus normally has 256 Kbyte of system memory (RAM) which should be supplemented with an additional memory board containing 384 Kbytes of RAM, for a total of 640 Kbytes. One vendor for the memory board is Quadram[5]. After the addition of the memory board, the Compaq Plus has four slots for other add-on boards. One of these will be used for the video digitizer.

Video Digitizers

In the course of this program, three video digitizers were evaluated for their suitability as a part of System I. All of these digitizers are on single printed circuit cards which can be plugged directly into an IBM-PC or a look-alike such as the Compaq. The three boards are manufactured by Imaging Technology[6], Datacube[7], and Coreco[8]. The nominal characteristics of each board are given in Table 1.

---

[4] Compaq Computer Corporation, PO Box 30, 19515 FM 149, Houston, TX 77070

[5] Quadram Corporation, 4357 Park Drive, Norcross, GA 30093

[6] Imaging Technology Incorporated, 600 West Cummings Park, Woburn, MA 01801

[7] Datacube, Inc., 04 Dearborn Road, Peabody, MA 01960

[8] Coreco Inc., 547 St. Thomas, Longueuil, Quebec, Canada J4H 3A7

TABLE 1. VIDEO DIGITIZERS

Manufacturer	H/V Resolution	No. of Gray Levels	Power Requirement
Coreco	512 H x 480 V	128	5V @ 4.0A -5, ±12V @.5A
Imaging Technology	512 H x 480 V	256	5V @ 3.0A ±12V @ .25A
Datacube	384 H x 480 V	256	5V @ 2.9A ±12V @ .25A

All three manufacturers use standard RS-170 video signals as both input to and output from their boards, with the exception of the video bandwidth required to maintain the horizontal resolution. Normal RS-170 (the broadcast standard) has a video bandwidth of 3.2 MHz, giving a horizontal resolution of about 250 T.V. lines. The first two boards in Table 1 have a video bandwidth in excess of 8 MHz, while the last is greater than 6 MHz.

The vertical resolution of standard RS-170 is 525 T.V. lines, but 7.5 percent of these are lost during the vertical retrace period. As a result the actual vertical resolution is only 480 TV lines. However, the optical resolution is lower than this because the horizontal traces are not perfectly straight, nor do they overlap. This has led to an experimentally developed "kell factor" of 0.7 to describe actual resolution, which is the number of lines displayed times the kell factor. This gives a vertical resolution of only about 350 lines; in a practical sense, the real resolution is somewhere between the two numbers (350 lines vs 480 lines).[9]

The discussion below gives an evaluation of each of these products in terms of spatial resolution, gray-scale resolution, software available for each, and a overall evaluation of the three.

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[9] Standardization of the Television Raster, John H. Harshbarger, Visual Information Institute, Inc., PO Box 33, Xenia, OH 45385

products in terms of spatial resolution, gray-scale resolution, software available for each, and a overall evaluation of the three.

Spatial Resolution

The RS-170 video standard calls for a 4:3 aspect ratio in the displayed picture; that is, the horizontal size of the viewed image is 1.33 times the vertical size. Using this figure, the approximate spatial resolution of the different boards can be predicted. Of course, the actual resolution may be somewhat lower than predicted, depending on the video camera used, the lighting conditions, and the contrast in the image.

If a 5.12 inch (13.00 cm) wide image is viewed with a video camera, the vertical size will necessarily be three-fourths of this (because of the 4:3 aspect ratio) or 3.84 inches (9.75 cm). Thus, the maximum horizontal resolution will be 0.010 inches (0.254 mm) for the two boards with 512 pixels in the horizontal direction, while the vertical resolution will range between 0.011 and 0.008 inches (0.279 mm and 0.203 mm). Thus for these boards, the resolutions in the two directions are about equal. On the other hand, the Datacube board, with only 384 pixels in the horizontal direction, has a maximum horizontal resolution for the same image of only 0.013 inches (0.330 mm), perhaps as much as 60 percent greater than the resolution in the vertical direction. To achieve the same resolution as with the other two boards, the image size must be reduced to 3.84 inches (9.75 cm) by 2.88 inches (7.32 cm). Thus, the Imaging Technology and Coreco boards can view almost 80 percent more area with the same efficiency as the Datacube board. All other things being equal, the Imaging Technology and Coreco boards are recommended over the Datacube on the basis of spatial resolution.

The resolution of the Imaging Technology board was measured with a Dage-MTI NC-65 camera attached (see the section below on Video Cameras), using a standard NBS resolution chart. This chart contains black horizontal and vertical lines of various spacings on a white background. The measured resolutions were 400 optical (not TV) lines in the horizontal and 370 lines in the vertical direction. The measured resolution in both directions is only about 78 percent of the theoretical

maximum, attributable to electrical noise, vibration of the camera, and the somewhat subjective nature of the measurement.

Gray-Scale Resolution

The analog video signal from the video camera ranges from 0.35 volts, representing "full black", to 1.0 volts, representing "full white". This signal is digitized by the video boards to a give a number representing the video signal level; these numbers can range from 0 to 255 in the case of the Imaging Technology and Datacube boards, and 0 to 127 for the Coreco board. Thus, for the Imaging Technology and Datacube boards, each increment (from 0 to 255) corresponds to a change of 2.54 mV in the analog video signal, but represents a change of 5.08 mV for the Coreco board.

For most video cameras, the definition of "full black" and "full white" depends on the image being viewed, the iris opening, the sensitivity of the light sensor in the camera, and perhaps, the gains of various electronic amplifiers in the camera or digitizer. Shown in Figure 2 are three curves relating film density to digitized gray-scale value for a Sony CCD camera with the Imaging Technology digitizer for three different light level ranges. Note that the scale for the gray-scale is logarithmic.

Since film density is defined as the logaritnm of the fraction of transmitted light intensity, while the gray-scale value is roughly proportional to the light intensity, a plot of gray-scale value versus film density should be linear on a semi-log plot. Indeed it is, at least until the gray-scale value drops below about 30, where a noticeable tail develops (due to offsets in the camera electronics). The slopes of all three curves should be the same, and again, they are approximately so. The equation for gray-scale value (G) as a function of film density (D) is given by

$$\log G = K + mD \qquad (1)$$

where K is some constant (determined by, among other things, the lens iris on the camera) and m is the slope of the curve. Generally, m is

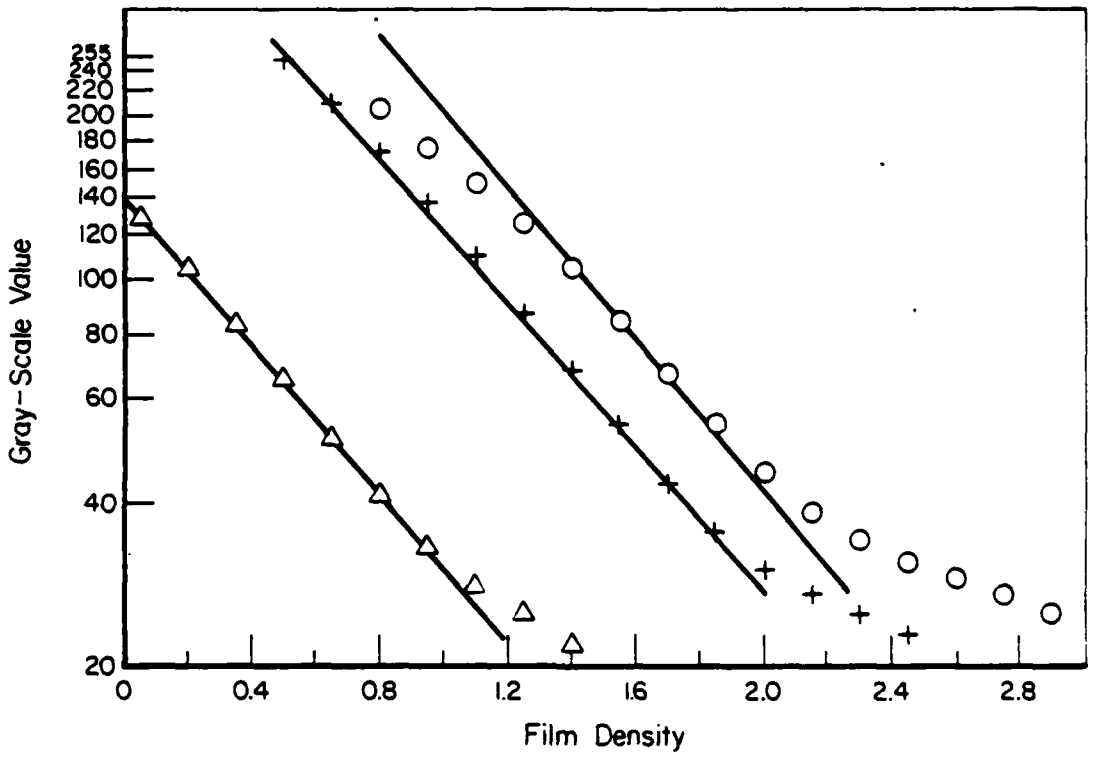

FIGURE 2. DIGITIZED GRAY-SCALE VALUES VERSUS FILM DENCITIES FOR THREE CAMERA IRIS SETTINGS

fixed for a particular camera, though some cameras will allow m to be adjusted. For the camera used in Figure 2, m is approximately -0.63.

To measure the sensitivity of the digitizer board to changes in film density, the derivative dG/dD is computed from Eq. 1, as

$$dG/dD = 2.3026m(K + mD) \tag{2}$$

or

$$dG/dD = 2.3026mG \tag{3}$$

Note that the rate of change of gray-scale with respect to film density depends on only two things, the gray-scale value and the camera constant. In this section, the discussion is concerned only with the digitizer boards, and the value for m will be treated as a constant. To evaluate the sensitivity to density changes it is noted that

$$\Delta G/\Delta D = dG/dD \tag{4}$$

or

$$\Delta D = \Delta G/2.2036mG \tag{5}$$

Since the gray-scale levels can only change in discreet levels of one, then smallest density difference than can be discerned is

$$\Delta D = 0.4343/mG \tag{6}$$

Table 2 shows the smallest discernible density difference for various gray-scale values using the straight-line approximation to gray-scale vs density curve. The actual ΔD's are a little larger for gray-scale values less than about 40, because of the tail in the curve.

TABLE 2. SMALLEST DISCERNIBLE DENSITY DIFFERENCES

G	ΔD
255	.003
200	.003
150	.005
127	.005
100	.007
70	.010
60	.011
50	.014
40	.017
30	.023

In the last report, it was shown that the difference in film density for an AWG #30 gage wire (0.010 inch or 0.254 mm diameter) behind 0.25 inches (6.35 mm) of steel may be as little as 0.01 for (reasonably) improperly exposed Polaroid film. To be able to distinguish this difference, it is necessary to position the "full white" level of the video camera somewhere near the density level for the steel itself. Otherwise, it will not be possible to discern these small density differences even with postprocessing of the gray-scale values. For example, if the gray-scale value for the steel alone were as low as 70, then the gray-scale value for steel plus copper wire would also be 70, and no type of postprocessing would be enable the two cases to be distinguished.

The above analysis assumed that there is no noise, either from the film or the electronics in the system. If the digitizer is only accurate to plus or minus one bit (normal for most digitizers), then the smallest discernible density difference is increased by a factor of two in the table above. The smallest density difference discernible by the human visual system is between 0.04 and 0.05, so the digitizer is better than a human, in the ideal case, by a factor of 15. If noise is present, this improvement may only be as large as a factor of 8, but this is still a significant improvement over the human visual response.

If the same analysis is made for the Coreco board (with only 128 gray levels available), it would be found that Table 2 still applies,

except that the gray-scale values are limited to 127 or less. Thus for this board, the minimum discernable density difference (with noise) is around 0.01, just adequate for the case of the wire behind steel.

On the basis of gray-scale resolution, the Imaging Technology and Datacube digitizers are superior to the Coreco. Moreover, the difference in gray-scale resolution is important for this application.

Software Requirements

The primary function of the software for System I is to allow the operator to enhance the contrast of video images. Other image processing functions will also be useful. Among these are edge sharpening to visually enhance thin objects such as wires, and time averaging the video signal to improve the signal-to-noise ratio and give a much cleaner image. Other useful functions not related to image processing are storing an original or processed image on disk or retrieving a stored image for further processing or review.

Software written by Battelle for the purposes of evaluating the Imaging Technology digitizer is included as Appendix A. Though not strictly intended to be easy to use, it contains most of the necessary functions and may be used as a guide to future software development.

Available Software

According to the manufacturers of all three digitizer boards, software can be supplied to operate their boards. This software is free with the Datacube board and available at an extra cost for the other two. It was possible to evaluate the software for the Datacube and the Imaging Technology boards. The software was not available (not yet written) for the Coreco board at the time of evaluation.

Datacube-Supplied Software. The software supplied by Datacube included a demonstration program along with several subroutines written for the Lattice C compiler[10]. These subroutines are used to setup the digitizer and acquire images. No image processing or contrast

[10] Lattice, Inc., PO Box 3148, Glen Ellyn, IL 60138

enhancement routines are supplied. Except for the routines which actually operate the board, all software for System I must be written.

Imaging Technology-Supplied Software. Unlike Datacube, Imaging Technology will supply a complete software package with their board (at a cost of $995). Their package is touted in the trade journals as the best available for the IBM-PC class computers. The author was supplied with both Version 1 and a preliminary copy of Version 2. Imaging Technology plans to provide a complete set of subroutines which can be integrated into a developer's program, but these were not available for evaluation.

According to the manual supplied with the software, ImageAction (the name of Imaging Technology's software package) contains a large set of image processing and image enhancement functions, including contrast enhancement functions. Unfortunately, all the functions which would have been useful for this application were marked "Not Implemented" in the Version 1 documentation. These functions were to be implemented in Version 2, but the majority of these would not operate correctly in the tested copy. It is assumed that a final copy of Version 2 will perform correctly. Other functions which did operate correctly were terribly slow. For example, the edge sharpening algorithm used by Imaging Technology required about 5 minutes to complete. A proper algorithm, written in assembly language, requires only about 45 seconds to perform the same function (see Appendix A).

The term "user-friendly" is much overused to describe software which is supposedly easy to use and, as importantly, easy to learn how to use. Imaging Technology lays claim to having user-friendly software. Most actions which their software performed can be selected without the use of the keyboard; instead, the operator uses a mouse to move a cursor on a menu to select various actions. Typically, selecting an item on the main menu causes ImageAction to bring up another menu, and so on, until some useful function is finally performed. There are something like a dozen and a half different menus which the operator must be familiar with before he can properly use ImageAction. It is not that menus are a bad choice for allowing the operator to control the actions of the software; it is more that ImageAction, which is a general-purpose

image processing package, is more complicated than necessary for the purposes of EOD teams.

ImageAction requires two separate video monitors, one the normal alphanumeric system monitor and the other for viewing the video image. For some reason, the authors of ImageAction decided to place the menus on the image monitor instead of on the system monitor. To do this, they only allow 128 gray-scale values for the image (the other 128 are reserved for drawing the menus), and not the full 256 of which the board is capable. As a result, the performance of the board is immediately down-graded to that achievable with the Coreco board, an unwise decision. Also, it is somewhat difficult to remove the menus from the image, though it is relatively easy to move them around on the screen. Thus, some portion of the video image is nearly always obscured by a menu.

ImageAction relies on the operator to properly set certain registers on the digitizer board, so not only must the operator be familiar with the software, but he must also have some degree of familiarity with the operation of the hardware. It is believed that the operator should be divorced from any knowledge of the actual hardware as much as possible.

In summary, ImageAction does provide all of the functions required by EOD teams (assuming that the final version works correctly), though in a package which is more difficult to use than it should be. The performance of the Imaging Technology digitizer is downgraded by their software package. At a cost of almost $1000 per copy, nearly $300,000 may be required to supply all EOD systems with a copy. It is believed that more usable software can be developed for a one-time cost which is far less than this.

Video Cameras

Four video cameras were evaluated during this program. These were a Sony[11] CCD-G5, a Pulnix[12] TM-34K, a Dage-MTI[13] NC-65S, and a

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[11] Sony Corporation of America, Sony Drive, Park Ridge, NJ 07656

[12] Pulnix America, Inc., 770-A Lucerne Dr., Sunnyvale, CA 94086

[13] Philips GmbH, distributed by Ridge, 4432 Bibb Boulevard, Tucker GA 30084

Dage-MTI NC-67M. The first two are representative of commercially available cameras using CCD arrays as the light sensing elements, while the third is representative of high resolution cameras with vidicon-type sensing elements. The last camera also uses a vidicon sensing element, but has variable black level and contrast controls external to the camera.

The evaluations performed on these cameras were limited by the amount of time they were on hand; for example, the TM-34K was available for only about three hours and the NC-67M for about one hour. The primary evaluation of the first three was a measurement of their spatial resolution, since that is the single-most important characteristic which will determine how well System I can resolve small objects (such as an AWG #30 wire).

The selection of the type of image sensor (CCD versus vidicon) depends on the type of application. The CCD arrays will function with extremely low light levels, have excellent spatial linearity, and are not subject to image lag or blooming. Vidicons, on the other hand, are not as sensitive to light, suffer somewhat from spatial distortions, are subject to "image burn" if overexposed for long periods of time, and suffer from both lag and blooming. The primary advantage of vidicons are their spatial resolution characteristics. The number of pixels in commercially available CCD arrays is about 384H x 480V, though some CCD's currently under development have resolutions as high as 1024H x 1024V. Resolutions greater than 500 pixels in the horizontal direction are not unusual for vidicons, and cameras with several thousand pixels are readily available.

To measure the resolution of the cameras, the cameras were used to image a NBS test chart on a video monitor. The measured resolution of the three cameras is listed in Table 3. Not surprisingly, the camera with a vidicon tube possessed significantly higher resolution. The measured resolutions for the two CCD arrays matched the manufacturer's claims reasonably well, but are slightly lower than claimed by the manufacturer for the Dage camera.

TABLE 3. MEASURED CAMERA RESOLUTIONS

Camera	Horizontal Resolution (Optical Lines)	Vertical Resolution (Optical Lines)
Sony CCD-G5	280	300
Pulnix TM-34K	280	325
Dage-MTI NC-65S	450	370

All three cameras with the Imaging Technology digitizer were able to successfully resolve small (believed to be AWG #24) wires in the radiographs supplied by NAVEODTECHCEN. However, only the Dage camera was able to resolve the smallest wires (believed to be AWG #30) in the radiograph. In terms of the rather subjective judgement of picture "quality", the NC-65S was obviously superior. The prices of all three cameras are approximately the same, in the $1100 to $1600 range.

Though no tests could be made with the Dage-MTI NC-67M camera, it was possible to image the NAVEODTECHCEN-supplied radiographs with this camera. The NC-67M has an external black level and contrast control which effectively adjusts the "full white level" and the camera constant m discussed in the section above on gray-scale resolution. With this camera connected directly to a video monitor and without any contrast enhancement added by the computer, it was possible to resolve most of the same features as seen with the NC-65S camera with contrast enhancement. The quoted horizontal resolution of this camera is about 1100 TV lines, commensurate with the approximately $3500 price tag. It would have been interesting to try this camera with the digitizer boards, but unfortunately, the digitizer boards had to be returned to the manufacturers before this could be done.

In summary, the two Dage-MTI cameras were obviously superior to the CCD array cameras in terms of spatial resolution. The Dage-MTI NC-65S and the two CCD cameras were subjectively judged to provide about the same level of contrast enhancement. The Dage-MTI NC-67M provided superior contrast enhancement with it's built-in contrast control and was judged the best in terms of the camera alone, but could not be evaluated in combination with the digitizers.

Logarithmic Amplification of the Video Signal

Film radiography is an inherently logarithmic process, where film density is proportional to the logarithm of X-ray exposure (equal to the product of the intensity and duration of the X-ray beam). If two objects are radiographed with two different exposures, the film densities of the two objects will be different for the two exposures, but the difference in film densities for the two objects will be the same in both exposures. The analog signal from a video camera is proportional to light intensity, and the difference in the analog video signal for the two objects will not be the same for the two different exposures, though their ratio will be. Thus, the same objects, radiographed twice with different exposures, may appear drastically different when viewed with a linear camera.

For this reason, the sensitivity of the digitizer to changes in film density is greater for small film densities than it is for high densities, as discussed above. A difference in film density which is visible at one density range may not be at another. A solution to this problem is to logarithmically amplify the video signal from the camera prior to the video digitizer. The sensitivity to density differences would then be uniform across the entire density range and small density differences would be as apparent at high film densities as at low densities.

The Light Table

The most effective means of illuminating the radiographs is with a light source on the opposite side of the film from the camera. The amount of light necessary will depend on the camera and the lens used. In the experiments conducted in this program, the radiographs were illuminated with 180 foot-lamberts. This light level was more than adequate for all of the cameras evaluated in this program.

Video cameras display an entire image in 1/30 of a second. Fluorescent lights have the disconcerting habit of turning completely off every 1/120 of a second, or four times for every image. Video cameras are fast enough to catch this and vertical bars can sometimes be seen in the image, especially during contrast enhancement. Incandescent bulbs are less bothersome in this respect, but still have a noticeable flicker. Please note that a difference in film density of 0.01 corresponds to a difference in light transmission of only 2.3 percent. To reduce the noise in the digitized image, the flicker should be less than this. Thus, it is recommended that incandescent light bulbs powered by a DC source be used to illuminate the radiograph.

This does mean, however, that the illumination across the light table should vary by less than this amount. Illumination variations have a relatively low spatial frequency, which the human eye is very good a filtering out. On the other hand, portions of the radiograph will be unviewable during contrast enhancement if the light level varies by too large an amount. It is recommended that the variation in illumination across the radiograph be no greater than 10 percent.

Recommended Equipment

The following equipment is recommended for System I.

1. Compaq Plus portable computer with integral monitor, 360 kB floppy disk, 10 MB hard disk, and 640 kB system RAM.
2. Imaging Technology digitizer board.
3. Dage-MTI NC-65S video camera.
4. Software to be provided by a third-party vendor.

System I Cost

The cost of the portable computer, including RAM add-on card, is approximately $4600. The Imaging Technology digitizer is approximately $3500. The Dage-MTI 65 series cameras cost between $1300 and

$2000, depending on the exact configuration; the one evaluated (NC-65S) in this program was about $1600. The total price, excluding software and the light table, will be between $9400 and $10,100. It is estimated that the software (amortized over 100 systems) and the light table together will cost under $1000. Thus, the total system price should be between $10,000 and $11,000.

Notes on Packaging

The envisioned System I will be contained in two portable containers which can be transported to the working site as carry-on luggage on commercial airliners. In order to do this, the size of the containers must fall within certain guidelines. These are that the sum of the length, depth and width of the container must be less than 45 inches (1.14 m). Nominal dimensions would be 21 inches (53.3 cm) x 16 inches (40.6 cm) x 8 inches (20.3 cm). The Compaq portable computer is already packaged to meet this criterion. One option for the second container is to buy a case similar to the Compaq's and modify it to contain the light table, camera, and camera lens.

DESIGN OF SYSTEM II

System II is mobile radiographic system containing sophisticated radiographic equipment, films, film developer and image processing/enhancement equipment. Unlike System I, System II is not designed to be readily portable. Instead, System II is housed in an air-transportable pod which can be loaded on military or commercial air transport and flown to the nearest landing field to the site. Once on the ground, System II will be loaded on a truck and moved onsite. Envisioned applications of System II are activities like screening packages entering Olympic Village at the 1984 Summer Olympics or rendering safe very complicated IED's where the allowable response time can be measured in days instead of hours. An example of the latter would be the IED at State Line, Nevada.

Because cost is a critical issue in the decision to pursue the development of System II, two versions were actually designed. Both versions contain exactly the same radiographic equipment, films, developer, and so on; the primary difference is the image processor and digitizer. System IIa includes the complete System I as the processor/digitizer, while System IIb uses a far more sophisticated, and expensive, image processor and digitizer. It is believed that most of the problems faced by EOD teams can be solved by the use of improved radiographic equipment with only relatively simple image processing requirements. Thus, it is the author's belief that System IIa is the system of choice for EOD teams. Should it turn out that the more sophisticated image processing capabilities are required, they can be easily added later since System IIa is a subset of System IIb. The only extra considerations in upgrading from System IIa to IIb is packaging the equipment in the same (or perhaps an additional) air-transportable pod.

The design philosophy behind System II is to give the EOD teams needed flexibility so that good radiographs can be obtained under adverse conditions. For example, the selected X-ray unit can generate X-rays with energies ranging from 32 kV to 320 kV. The lower energies are useful for radiographing objects with low densities (plastics, wood, etc)

while the higher energies can be used to penetrate over an inch of steel. A variety of X-ray films were selected which have a much higher density range than the Polaroid film used with the flash X-ray unit. The higher density range of these films makes them more forgiving to overexposure witnout seriously degrading image quality. Since the development of X-ray films is somewhat tedious, an automatic film developer was also included. An image intensifier, which puts out a real-time video image suitable as input to the image processing equipment, was included so that the team can view the IED's at different X-ray energy levels without having to go through the process of developing films. And so on.

An artist's sketch of the components of System IIb is shown in Figure 3, while Figure 4 shows an artist's conception of the system in the pod. The X-ray unit would be removed through a side door to give the operator a place to sit in front of the image processing unit. System IIa would look similarly, except that System I would replace the digitizer and image processing units shown in Figure 4.

Functional specifications for System IIa follow, with additional specifications for System IIb afterwards. The remainder of this section discusses the selected equipment and the expected costs of both versions.

One note is in order. Because of the complexity, size, and cost of the equipment involved in System II, this was necessarily a "paper" design. That is, the selected equipment was not actually evaluated as was done for much of the equipment in System I.

System IIa Functional Specifications

Purpose: The primary purpose of Radiographic Enhancement System IIa is to provide a flexible and powerful radiographic system for use by EOD teams.

1. System IIa shall consist of a hot filament X-ray unit, various radiographic films, a film developer, an image intensifier, and the System I image enhancement system.

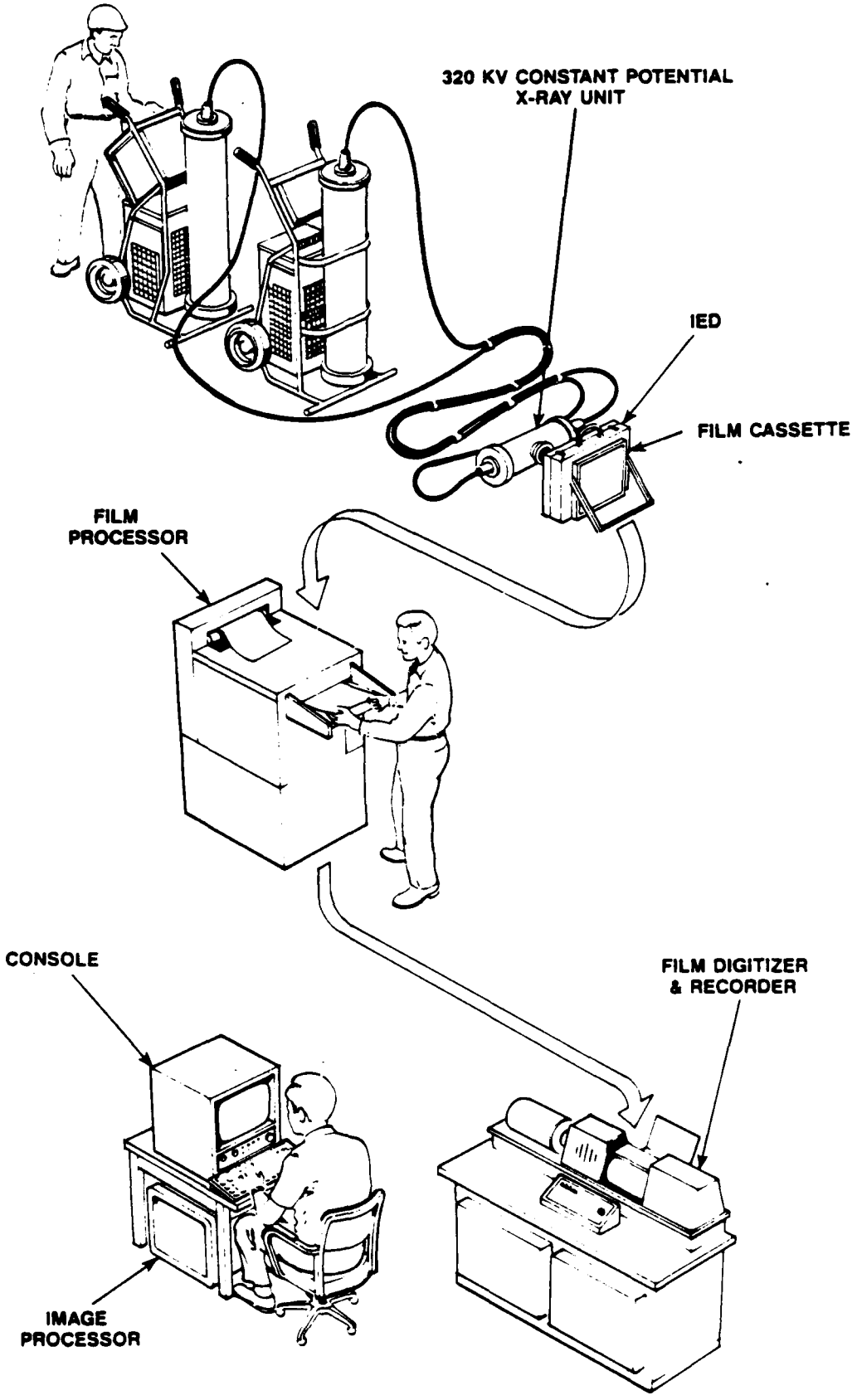

FIGURE 3. ARTISTS'S SKETCH OF THE COMPONENTS OF SYSTEM IIb

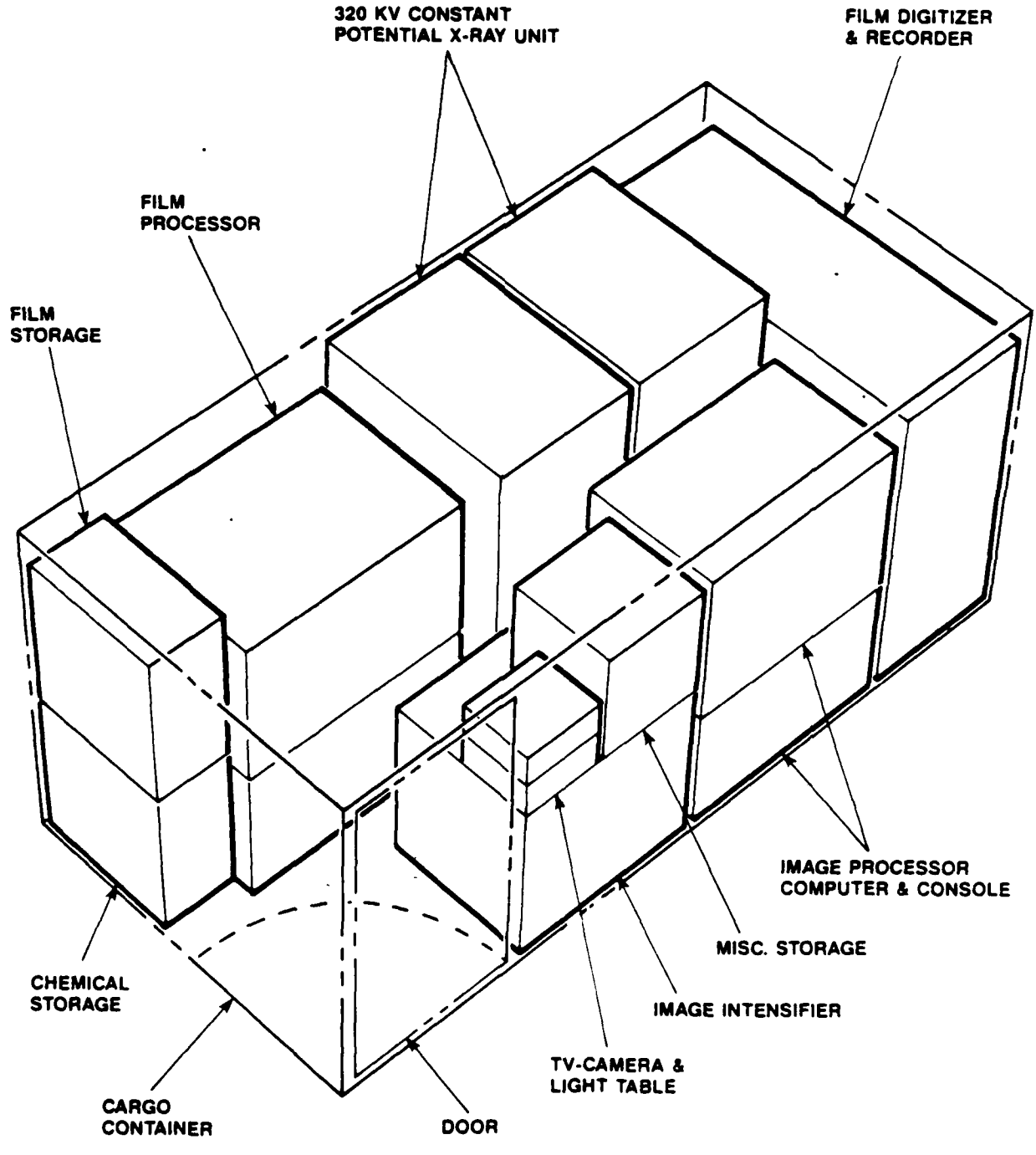

FIGURE 4. ARTISTS'S CONCEPTION OF SYSTEM IIb IN THE AIR TRANSPORTABLE POD

2. The hot filament X-ray unit shall be capable of generating X-rays with energies ranging from 32 kV to 320 kV, as a minimum. Sufficient X-ray tube heads will be included to cover the range of available energies. The working distance from the X-ray tubes to the unit's control panel shall be at least 50 feet. The control panel shall be able to control the voltage and current to the X-ray tube, and shall contain some means of automatically timing the X-ray exposure. The X-ray unit shall be mounted on a self-contained cart, and a mobile tubestand shall be provided to position the X-ray tube with respect to the target.

3. The radiographic film shall be commercially available radiographic film meeting ASTM Type I, Type II, and Type IV descriptions. These films shall be suitable for automatic film processing. Standard sizes, in inches, will be 5x7, 8x10, 11x14 and 14x17. Lead screens in 0.005 and 0.010 inch thicknesses, intensifying screens, and film cassettes for each film size shall also be provided.

4. The film processor shall be compatible with the radiographic films provided under Item 3. The processor shall be require only a cold water feed at less than 1 gallon per minute (processing) and 0.1 gpm (standby).

5. The image intensifier shall be able to image an area at least six inches in diameter, and shall provide a high quality, high resolution (approximately 400 horizontal TV lines) RS-170 output suitable for the System I video digitizer.

6. The image processing system shall be a complete System I as described above. One additional software requirement

is that the system must be able to store two images from the image intensifier (made using different energy X-rays) in memory and perform subtractive radiography as described in our previous report.

7. System II shall be housed in an air-transportable pod suitable for shipment on both commercial and military aircraft.

Additional Specifications for System IIb

8. The advanced image processing/enhancement system shall be comprised of a high resolution digitizer, digital processor to perform image enhancement, and a high resolution output device capable of making a hard-copy of the enhanced image.

9. The image digitizer shall be capable of digitizing at least a 10 x 10 inch film with densities ranging from 0.0 to 3.0 with at least 256 gray levels. The maximum spatial resolution of the digitizer shall be 1000 points per inch, the minimum requirement is 100 points per inch.

10. The image processor shall be capable of accepting images from either the high-resolution digitizer or from a standard RS-170 video signal. The processor shall be capable of performing all of the standard functions of System I. In addition, the processor shall
    a. perform subtractive radiography of images from either the high-resolution digitizer or the image intensifier
    b. perform image restoration and deblurring algorithms
    c. be capable of accepting images digitized and stored on System I.

11. The image output recorder shall be capable of recording images generated by the image processor with gray levels and spatial resolutions equivalent to the high-resolution digitizer. If the recording medium is film, then the film must be compatible with the film processor described in Item 4.

12. The image digitizer, processor, and recorder must be housed in either the same or a similar air-transportable pod as the rest of System II. At the site, the pod must open up to provide a comfortable working area for the EOD teams.

System II Hardware

System II contains a hot-filament X-ray unit, a variety of radiographic films, a film developer, image intensifier, and an image processing unit. Specific equipment selections for these components are described below. In several cases, only one source for the equipment is indicated; comparable units from other manufacturers would suffice.

X-Ray Unit

To give added flexibility to the EOD teams, System II includes a conventional hot-filament X-ray unit which can generate X-rays with energies ranging from approximately 30 kV to over 300 kV. This range will allow high quality radiographs of a variety of targets.

The contrast available in a radiograph depends strongly on the X-ray energy used. Low density objects, such as woods, plastics, etc. are best radiographed with low energy X-rays (30 to 100 kV), while thick sections of dense materials such as steel require X-rays with high penetrating power (100 to 300 kV). All of these objects can be radiographed with a single, variable energy unit, though not necessarily at the same time.

To generate the high voltages necessary to drive the X-ray tubes, an alternating current is sent to a high voltage transformer, which generates the necessary voltage. This voltage is rectified and sent to the tube. If the voltage is unfiltered, then the voltage across the tube varies from some maximum value to zero; the net result is that X-rays of all energies are generated. In general, this will produce an inferior radiograph. Newer, constant-potential units filter the voltage applied to the tube, with the result that the X-rays generated have a more uniform characteristic. Typically, useful X-ray production is 30 percent higher with a constant potential system as compared with an unfiltered system. The increased production allows the current to the tube to be reduced with a concomitant reduction in the focal spot size. The result is a far superior radiograph.

A good constant-potential X-ray unit is the Philips[14] MG 321L 320 kV X-ray system. The unit is housed on two carts which are moved to the site and then connected with a cable. Contained on the carts are the controller, high voltage generators, and integral oil cooling system for the X-ray tube. The tube (MCN 322) is capable of generating X-rays in the range of 30 to 320 kV, and can be used to expose up to 3 inches of steel with exposure times of about 15 minutes. The tube has a dual focal spot size of 1.8 mm and 0.8 mm (at reduced current levels). The tube can be situated up to 65 feet from the control unit. The MG 321L can also use a MCN 166 X-ray tube, which gives a finer focus (down to 0.4 mm), with X-ray energy up to 160 kV.

The cost of the MG 321L is approximately $60,000.

Radiographic Films

Good quality radiographic films allow significant leeway in exposure while still producing high-quality radiographs. This is primarily because radiographic films have usable density ranges ranging from about 0.5 to well over 6. There are many suppliers of films; the

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[14] E. I. duPont de Nemours & Co. (Inc.). Photo Products Department. Wilmington, DE 19898

most often used in this country are Kodak and DuPont. It is suggested that one of these two sources be used since the film is readily available in any part of the country. DuPont films will be used as an example.

DuPont makes seven different radiographic films with varying degrees of contrast, graininess, and speed. These films are denoted NDT 35, 45, 55, 65, 70, 75, and 91. The first four are low speed, very high contrast with very low graininess. The next two are medium speed, high contrast with low graininess, and the last is very high speed with high contrast and graininess. The films come in a variety of sizes; the most useful will probably be 5x7, 8x10, 11x14 and 14x17. System II should have a complete selection of each type and size. DuPont films are well suited to automatic processors.

Because each film type has a different speed (sensitivity to X-rays) a common technique used to radiograph an object with widely varying densities is to place two or more films inside one film pack. Thus, the thinner or less dense sections are viewed on the slower film, while the thicker or denser sections are viewed on the faster films.

DuPont, as do other manufacturers, can also supply a wide range of lead and fluorescent screens, and film cassettes. These items should also be obtained for System II. The total cost for films, cassettes, and screens will be in the neighborhood of $7000.

Film Processor

Developing radiographic film is not exceptionally difficult, though it does require a dark room with chemicals maintained at carefully controlled temperatures. This necessity can be avoided by using a film processor which automatically develops the film without the need for a darkroom. The better processors require only cold water and electricity, along with the appropriate chemicals. Water requirements are typically less than 1 gallon per minute.

Development times vary depending on the type of film, but a fully developed and dried film can usually be produced in less than 15

minutes. Two representative processors are the DuPont[15] Cronex NDT 100 and the Alphatek[16] AX-700. Both processors are available for less than $10,000, including chemicals.

Image Intensifier

Image intensifiers represent a different imaging source for radiographic procedures. The advantages of intensifiers are real-time imaging and an output which is RS-170 compatible and can be input to the image processor directly without going through the film development and digitization. Disadvantages are their relatively large size, precluding their placement behind all objects, relatively small viewing area (up to about 10 inches in diameter), and higher graininess in the image as compared to film. Thus, intensifiers are not a replacement for film radiography, only an adjunct.

Several uses we can see for the intensifier are examining packages very quickly, viewing an object with X-rays of varying intensity and energy, and providing the images for the subtractive radiography. Image intensifiers are supplied by a variety of companies, including DuPont and Ridge[16].

Additional Equipment for System IIb

As we discussed above, the difference between Systems IIa and IIb are the image digitizer and image processor. System IIa uses the equipment detailed under System I as the digitizer/processor. System IIb has, in addition to System I, a high resolution digitizer and recorder and a high-speed image processor. These are detailed below.

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[15] Alphatek Corporation, 650 W. Lake Street, Chicago, IL 60606

[16] see 13 above.

Image Digitizer and Recorders

The main drawback of the image digitizer in System I is the relatively low spatial resolution, nominally 512 pixels in each direction. If an entire 8 x 10 inch radiograph is digitized with this system, the pixel resolution is about 0.02 inches. We believe that, for some applications, spatial resolutions of 0.005 to 0.010 inches may be required. With System I, this can be obtained only by decreasing the field of view to about one-fourth to one-half of the radiograph at any one time.

One other drawback of System I is that there is no way to make a permanent hard-copy of the enhanced image. Thus, to work on the IED (to place shaped charges, for example), the image processing system or a separate video monitor must be carried near to the IED.

Both of these drawbacks can be solved by including a high-resolution film digitizer/recorder with System IIb. The only available device with this capability is the Optronics[17] P-1700 Photomation Scanner (digitizer) and Recorder. This model can digitize up to 10 inch x 10 inch film images with variable spatial resolutions ranging from 25 microns (0.001 inches) to 400 microns (0.016 inches) in steps which differ by a factor of two. At the highest resolution available, an 8 x 10 inch radiograph would give about 80 million pixels, far more than most computers can handle at any one time. With resolutions which are more useful for this application (100 or 200 microns), the same radiograph will give us between one and five million pixels. Though these are still large numbers, they can be handled by most of the newer microprocessors.

The gray-scale resolution of the digitizer is one part in 256. However, this can be selected to be either a linear scale (like the video cameras) or a logarithmic scale. The advantage of the latter scale is that the density resolution of the digitizer is constant and does not drop off at the lower density ranges as it does with the linear scale. For the logarithmic scale, the density resolution can vary from 0.004 to 0.011, in three steps. In the linear mode, each step in gray-scale

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[17] Optronics International Inc., 7 Stuart Road, Chelmsford, MA, 01824

corresponds to a difference in light transmission of 0.39 percent, with a minimum value of 0.25 percent and a maximum of 100 percent. The density resolution in the linear mode ranges from 0.41 at the low end of the gray-scale to 0.002 at the high end.

The Optronics digitizer is not a real time device, since the maximum data taking rate is 32000 points per second. If the resolution is 100 microns, an 8 x 10 radiograph can be digitized in something less than 3 minutes. Though slow, this time is judged to be reasonable.

The film recorder side of the P-1700 is very similar to the digitizing side. The resolutions (both spatial and gray-scale) as well as the data rates are exactly the same; the only difference is that instead of measuring the light transmitted through the film, the film is exposed with varying amounts of light. This film will then be developed with the film processor included with System II to give a one-to-one copy of the enhanced image which can be used by the EOD teams while rendering the IED safe.

Samples of original and enhanced radiographs made with the P-1700 scanner are shown in Figures 5 and 6. The improvement in image quality is excellent. The streaks in Figure 6 are due to the coating applied to the original Polaroid film after development.

The Optronics P-1700 costs approximately $110,000.

Image Processor

The larger amounts of data that are generated by the Optronics scanner preclude the use of the System I image processor to enhance these images; the amounts of data that must be handled are simply to large to be processed in any reasonable amount of time. Thus, a higher speed processor must be used.

Since System II must fit inside an air-transportable pod, we can not use any of the image processors which are based on either minicomputers or mainframe computers; their size, weight, and cooling requirements are too severe to be met by a transportable package. Thus, we are left with the microprocessor-based machines. The major requirements which these machines must meet are (1) be able to interface to the

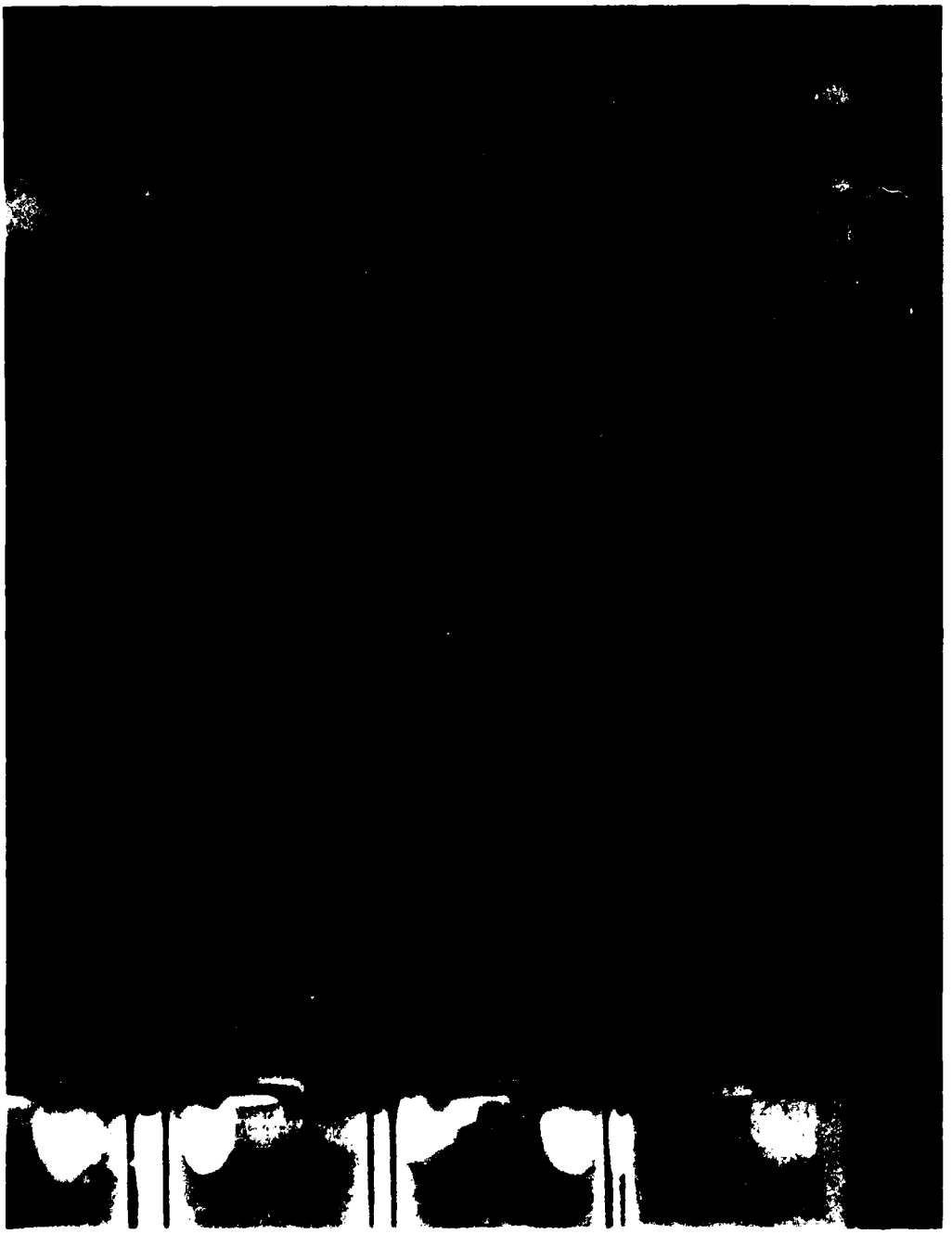

FIGURE 5. PRINT OF ORIGINAL UNENHANCED NEGATIVE SCANNED WITH THE P-1700

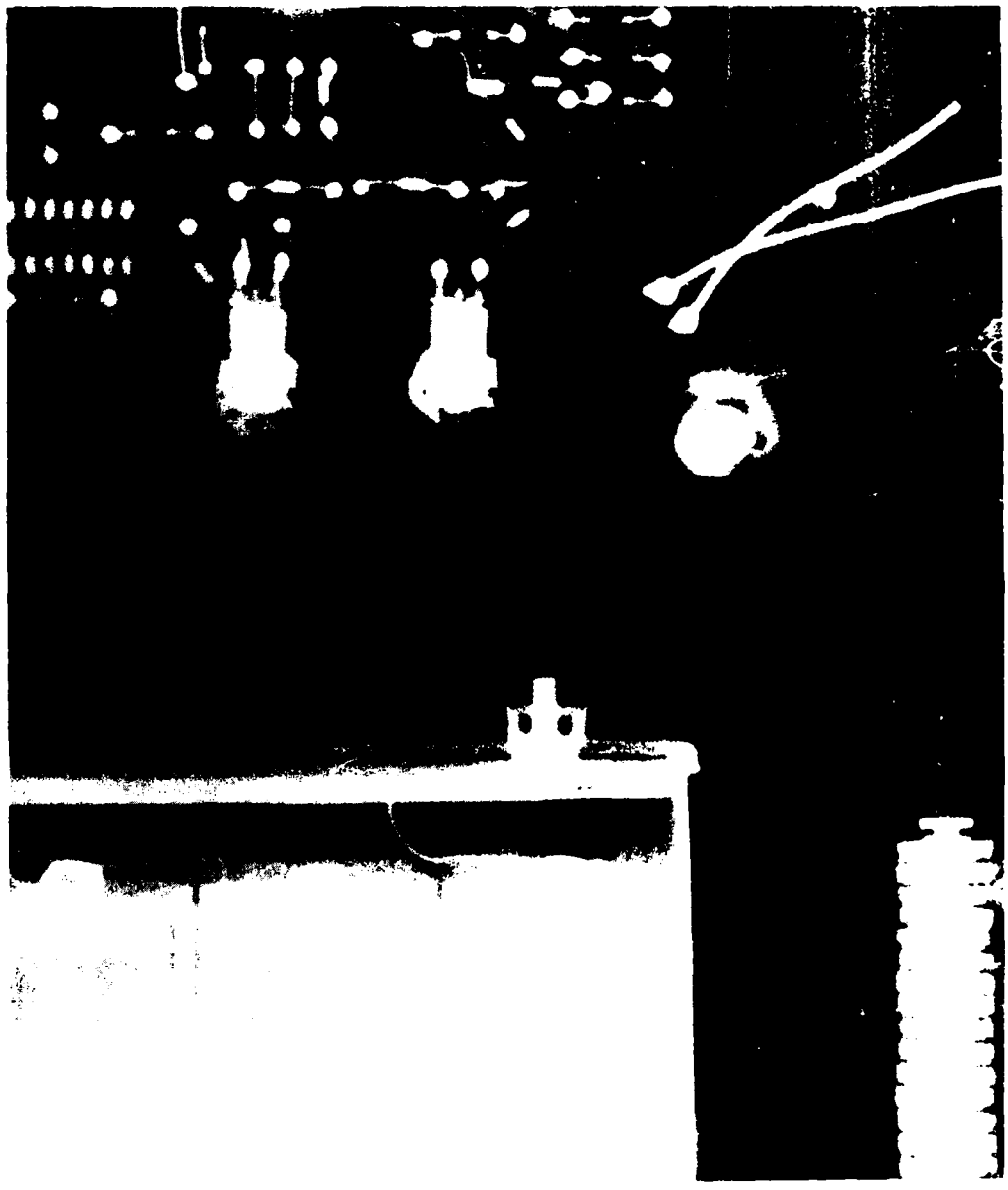

FIGURE 6. PRINT OF DIGITALLY ENHANCED IMAGE IN FIGURE 5 RECORDED ON THE P-1700

Optronics scanner, (2) be able to handle several megabytes of image memory, (3) perform computations quickly, and (4) use a well-known system bus for which other peripheral equipment is available.

There are three major families of microprocessors which might meet these requirements; these are the Intel[18] 80286, the DEC[19] MicroVAX II, and the Motorola[20] 68000.

The Intel 80286 is the big brother of the Intel 8088, the microprocessor used in System I. The major differences between the 80286 and the 8088 are larger instruction set, higher speed, and increased memory handling requirements. Because the instruction set of the 8088 is a subset of the 80286, a programmer familiar with the 8088 can easily learn the additional instructions of the 80286. In fact, many compilers that run on the computer used in System I can be used to generate programs for the 80286, a strong advantage. The 80286 can support up to 16 Mbytes of memory, sufficient to hold somewhere between 3 and 12 images generated by the Optronics scanner. The 80286 is available on the Multibus, which is well supported by add-on peripherals.

The DEC MicroVAX II is a new microprocessor which is nearly functionally equivalent to the DEC VAX line of minicomputers. The MicroVAX can address up to 9 Mbytes of memory, the equivalent of 1 to 6 images. With an added numerical processor, the MicroVAX can in most situations perform computations at speeds 80 to 90 percent of the VAX 11/780. The MicroVAX will run most of the software written for the VAX; there is probably more software written for the VAX than any other minicomputer, so that the MicroVAX, unlike other microprocessors, started out with an extremely large software base. The MicroVAX is available on the DEC Q-bus, also supported by an extremely large number of add-on peripherals.

The Motorola 68000 is one of the most popular 32-bit microprocessors on the market today. Like the Intel chip, it can support up to

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[18] Intel Corporation, 3065 Bowers Ave., Santa Clara, CA 95051

[19] Digital Equipment Corporation, 2 Iron Way, Marlboro, MA 01752

[20] Motorola Semiconductor Products Inc., 3501 Ed Bluestein Blvd., Austin TX 78721

16 Mbytes of memory, and with an added numerical processors can reach speeds comparable to the MicroVAX. Though relatively new, the 68000 is available on several buses, including Multibus and the VME bus. Both are well supported by vendors of add-on peripherals. Because the 68000 is relatively newer, its software base is not as large as for the MicroVAX.

The selection of an image processor based on one of these microprocessors can not be made on the basis of cost; a system built around any one of them will cost between $50,000 and $75,000 depending on the exact configuration. In terms of speed, the MicroVAX and the 68000 are roughly equivalent and better than the 80286. The MicroVAX has a much larger software base than does either of the two, and in fact, image processing software is available for the VAX already. Since with any computer system, the cost of software development far outweighs the cost of the system itself, and since DEC has service groups scattered throughout the country that can provide overnight service for most hardware problems, our first choice would be the DEC MicroVAX II and our second the Motorola 68000.

Hardware Requirements for System IIb. Besides the processor, memory, and mass storage (hard disks and magnetic tape), the image processor should contain a video digitizer and a high resolution video monitor capable of displaying at least 1024 by 760 images with 256 gray levels. Imaging Technology is one example of a company that can supply both of these products.

Software Requirements for System IIb. In addition to all of the functions provided by System I, System IIb should provide the following functions:

(1) Accept images digitized by the Optronics scanner.
(2) Send enhanced images to the Optronics recorder.
(3) Accept digitized images stored on the System I processor for subsequent processing.
(4) Digitize images from either the video camera or image intensifier.
(5) Perform subtractive radiography as described in our last report.

(6) Perform deblurring to remove blur in radiographs caused by the finite focal spot size of the X-ray beam or by large object-to-film distances.

System IIa Costs

The following represent our best estimate for the costs associated with assembling System IIa.

System I Image Processor (includes video camera and light table)	$10,000
Film Processor	$10,000
Philips MG321L X-Ray Unit	$60,000
Image Intensifier	$25,000
Various X-ray Films, Cassettes and Screens	$ 7,000
30 Amp, 220 V generator	$ 3,000
Air-transportable pod	$30,000
Additional Software Development (amortized over three systems)	$ 5,000

The total estimated cost for System IIa is approximately $150,000.

System IIb Costs

The additional hardware costs for upgrading System IIa to IIb is $110,000 for the Optronics scanner/recorder and $75,000 for the image processor. The estimated total cost, excluding software, is approximately $335,000. Purchased software may be as much as $50,000 per system, while specially-written software (subtractive radiography, data transfer from System I to System II, etc) will be about $10,000 per system. Thus, the total cost of system IIb is estimated to be $400,000.

CONCLUSIONS AND RECOMMENDATIONS

The design of two radiographic enhancement systems for EOD teams are discussed in this report. The first, System I, is an image enhancement system that can increase the contrast and clarity of radiographs made using the existing EOD X-ray system. System II offers improved radiographic capability through the use of a conventional hot-filament X-ray unit and radiographic films as well as an improved image processor.

Both systems will significantly increase the radiographic capabilities of EOD teams. System I, designed to be transportable as carry-on luggage on commercial airliners, will be carried by EOD teams along with existing EOD radiographic equipment in a rapid deployment mode. System II, because of its larger size and weight, is housed in an air-tranportable pod for situations that require radiographic capabilities beyond those of System I. As many as 300 copies of System I may be required to equip all EOD teams, while only three copies of System II, located at strategic positions in the United States, will be necessary. The expected cost of System I is approximately $10,000, while the expected cost of System II will range from $150,000 to $400,000, depending on the exact configuration selected. The lower cost is for System IIa, which uses the image processing capability of System I, while the higher cost is for System IIb, which includes an image processing system with much greater capability.

The fabrication of both Systems I and II are technically accomplishable with primarily off-the-shelf equipment. Items which cannot be purchased directly are the light table for System I, the air-transportable pod for System II, and all or portions of the software for both systems.

Our recommended course for the development of these systems is as follows. First, a prototype of System I should be built and tested under actual field conditions. Once this is completed, and assuming that the outcome is as positive as we believe it will be, then full-scale procurement of System I can begin. The next logical step would then be

to build and evaluate a prototype of System IIa, since it is a logical extension of System I. The development of System IIb, a superset of System IIa, would then follow should it be deemed necessary.

In the course of building the prototype of System I, we also recommend that development of a logarithmic amplifier for preprocessing the analog signal from the video camera be undertaken. This step should significantly improve the ability of System I to enhance poor contrast radiographs.

APPENDIX A

IMAGE PROCESSING SOFTWARE

for

THE IMAGING TECHNOLOGY FRAME GRABBER

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```
/*
 * the following routines control the Imaging Technology PCVision
 * frame grabber.  Image enhancement functions are selected by pressing
 * function keys on the IBM-PC keyboard.  Contrast enhancement is
 * controlled with the joystick
 */

#include "f:stdio.h"
#include "f:funckeys.h"

#define   EDGE          0
#define   LAPLACE       1
#define   SOBEL         2
#define   ROBERTS       3
#define   SALTNPEPPER   4

main()
     {
     extern int xjoy, yjoy, jswitch;
     unsigned char *databuf, *calloc();

     init();
     databuf = calloc(3 * 512, sizeof (*databuf) );
     /* stay in this loop until a ^C is pressed */

     for( ; ;)
          {
          /* first check for function key pressed /*

          switch (conin())
               {
               case F1: grab(0); filter(databuf, EDGE); break;
               case F2: grab(0); filter(databuf, LAPLACE); break;
               case F3: grab(0); filter(databuf, SOBEL); break;
               case F4: grab(0); filter(databuf, ROBERTS); break;
               case F6: grab(0);
                    filter(databuf, SALTNPEPPER, 32); break;
               case F7: grab(1); break;
               case F8: grab(0); break;
               case F9: copyotoi(); break;
               case F10: xjoy = 0; yjoy = 255; break;
               case ALTF10: invert(); break;
               case CTRLF10: average(); break;
               case 'r' : grab(0); readbuf(); break;
               case 'w' : grab(0); writebuf(); break;
               case 3:  return;
               default: break;
               }
```

```
            * now do contrast enhancement *

            gamecort();
            if (yjoy == 1)
                 yjoy = 1;
            if (yjoy > 255)
                 yjoy = 255;
            if (xjoy < 0)
                 xjoy = 0;
            if ((xjoy + yjoy) > 255)
                 xjoy = 255 - yjoy;
            lingray(xjoy, xjoy+yjoy);

            /* show the operator the max and min gray levels */
            if (jswitch)
                 printf("start %5d width %5d\n", xjoy, yjoy);
            }
      }

writebuf()
      {
      /*
      this function should write the image out to a disk file
      */
      }

readbuf()
      {
      /*
      this function should read an image from a disk file
      */
      }
```

```
/* perform temporal averaging */
average()
     {
     unsigned int ptr, j;
     unsigned int data[256];
     int file, temp, i, buff;
     unsigned char *dat, *abstoptr(), pixel[256];

     file = creat("f:temp.dat", BWRITE);
     if (file < 0)
          return;
     grab(1);
     dat = abstoptr(0xd0000L);      /* 0xd0000 is the start of the frame
                                       grabber memory */
     for (buff = 0; buff < 4; buff++)
          {
          printf("averaging bank %d\n", buff);
          setbuff(buff);
          for (j = 0; j < 256; j++)
               {
               for (temp = 0; temp < 256; ++temp)
                    data[temp] = 0;
               for (i = 0; i < 16; ++i)
                    {
                    ptr = j * 256;
                    for (temp = 0; temp < 256; ++temp)
                         data[temp] = data[temp] + dat[ptr++];
                    }
               for (temp = 0; temp < 256; temp++)
                    pixel[temp] = data[temp] >> 4;
               write(file, pixel, 256);
               }
          }
     grab(0);
     close(file);
     file = open("f:temp.dat", BREAD);
     printf("writing data to screen\n");
     for(buff = 0; buff < 4; buff++)
          {
          setbuff(buff);
          for(j = 0; j < 256; j++)
               read(file, &dat[j * 256], 256);
          }
     close(file);
     unlink("f:temp.dat");
     }
```

```
#define PCVBASE 0XFF00
#define CSRLOW PCVBASE
#define CSRHI  CSRLOW + 1
#define LUTADD PCVBASE + 2

#define LUTDAT PCVBASE + 3
#define MASKREG     PCVBASE + 4
#define BLKREG PCVBASE + 5

/* copy the output lookup table to the input lookup table */
copyotoi()
     {
     int i, dat;

     for (i = 0; i < 256; ++i)
          {
          outportb(CSRLOW, (inportb(CSRLOW) & 0XF9) | 2);
          outportb(LUTADD, i);
          dat = inportb(LUTDAT);
          outportb(CSRLOW, (inportb(CSRLOW) & 0XF9) | 6);
          outportb(LUTDAT, dat);
          }
     }

/* invert the input lookup table */
invert()
     {
     int i;

     outportb(CSRLOW, (inportb(CSRLOW) & 0XF9) | 6);
     for(i = 0; i < 256; ++i)
          {
          outportb(LUTADD, i);
          outportb(LUTDAT, ~inportb(LUTDAT));
          }
     }

/* either start (count != 0) or stop (count = 0) the digitizer */
grab(count)
     {
     if (count)
          outportb(CSRLOW, 0x3B);
     else
          outportb(CSRLOW, 0x2B);
     }
```

```
/* initialize digitizer and lookup tables */
init()
     {
     int i,j;

     outportb(CSRLOW,0x8);
     outportb(CSRHI,0);
     for ( i = 0; i < 256; ++i)
          {
          outportb(LUTADD, i);
          for (j = 0; j < 4; j++)
               {
               outportb(CSRLOW, (inportb(CSRLOW) & 0XF9) | (j << 1));
               outportb(LUTDAT, i);
               }
          }
     outportb(CSRLOW, 0X3B);
     outportb(MASKREG, 0);
     }

/* make one of the four memory buffers resident */
setbuff(buff)
     int buff;
     {
     outportb(BLKREG, buff);
     }
```

```
/* modify output lookup tables */
/* this function is the heart of the contrast enhancement */
linGray(imin, imax)
     unsigned int imin, imax;
     {
     unsigned val, i, j;
     static unsigned int oldmin = (0), oldmax = (255);

     if (imin < 0)
          imin = 0;
     if (imax > 255)
          imax = 255;
     if (imin >= imax)
          imin = imax - 1;

     /* if the same values, don't do anything */
     if ((oldmin == imin) && (oldmax == imax))
          return;

     /* 0 to imin -> 0 */
     for (i = 0; i < imin; i++)
          {
          outportb(LUTADD, i);
          for (j = 0; j < 3; j++)
               {
               while (!(inportb(CSRHI) & 0x4))
                    ;
               outportb(CSRLOW, (inportb(CSRLOW) & 0xF9) | (j << 1));
               outportb(LUTDAT, 0);
               }
          }

     /* imin to imax -> 0 to 255 */
     for ( ; i < imax; i++)
          {
          outportb(LUTADD, i);
          val = 255 * (i - imin);
          val /= (imax - imin);
          for (j = 0; j < 3; j++)
               {
               while (!(inportb(CSRHI) & 0x4))
                    ;
               outportb(CSRLOW, (inportb(CSRLOW) & 0xF9) | (j << 1));
               outportb(LUTDAT, val);
               }
          }
```

```
/* imax to 255 -> 255 */
for ( i : i < 256; i++)
     {
     outportb(LUTADD, i);
     for (j = 0; j < 3; j++)
          {
          while (!(inportb(CSRHI) & 0x4))
               ;
          outportb(CSRLOW, (inportb(CSRLOW) & 0XF9) | (j << 1));
          outportb(LUTDAT, 255);
          }
     }
oldmin = imin;     oldmax = imax;
}
```

```
int xjoy = (0);      /* joystick x position */
int yjoy = (255);    /* joystick y position */
int jswitch = (0);   /* joystick buttons */

/* use gameport adaptor to control contrast enhancement */
gameport()
     {
     long joyst(), xy;
     int x, y;

     xy = joyst();          /* assembly language routine to
                               find joystick position*/
     x = ((xy >> 16) & 0xffff) - 32;
     y = (xy & 0xffff) - 32;
     if (x > 20)
          xjoy += (x - 20)/4;
     else if (x < -20)
          xjoy += (x + 20)/4;
     if (y > 20)
          yjoy += (y - 20)/4;
     else if (y < -20)
          yjoy += (y + 20)/4;
     jswitch = ^inportb(0x201) & 0x30;
     }
```

```
/* direct console input/output routines */

static struct
          {
          unsigned char al,ah;
          int bx,cx,dx,si,di,ds,es;
          } regs;

static _conin()
          {
          regs.dx = 0xff;
          regs.ah = 6;
          return sysint21(&regs,&regs);
          }

conin()
          {
          if(_conin() & 0x40)
               return 0;
          if(!regs.al)
               {
               _conin();
               return regs.al + 256;
               }
          return regs.al;
          }

conout(c)
          int c;
          {
          regs.dx = c;
          regs.ah = 6;
          sysint21(&regs,&regs);
          }

constr(str)
          char *str;
          {
          while (*str)
               {
               if (*str == '\n')
                    conout ('\r');
               conout (*str++);
               }
          }
```

```
;
;       Video filter ros for the Imaging Technology PC vision
;       frame grabber
;
        include   f:model.h
        include f:prologue.h
;
;
abs     macro     reg
        local     abs1
        or        reg,reg
        jge       abs1
        neg       reg
abs1:   nop
        endm
;
negadd  macro     parm1
        mov       al, parm1
;       assume that ah = 0 already
        sub       bx, ax
        endm
;
accbx   macro     par
        mov       al,par
        mov       ah,0
        add       bx,ax
        endm
;
;       screen memory and I/O locations
SCNMEM  equ       0D000h
SCNBNK  equ       0FF00h+5
;
;       parameters on stack
BUFOFF  equ       @ab
BUFSEG  equ       @ab+2
FFUNC   equ       @ab+4
OPT     equ       @ab+6
;
;       automatic variables
RBCNT   equ       -2
ROW     equ       -4
COLUMN  equ       -6
SDPNT   equ       -8
FUNC    equ       -10
AUTO    equ       -12
;
;       row/column data reference in the row buffer
D00     equ       0
D01     equ       1
D02     equ       2
D10     equ       512
D11     equ       513
D12     equ       514
D20     equ       1024
```

```
D21         equ         1025
D22         equ         1026
;
;
;           c callable image filtering routines
;
;           syntax:
;           filter(buffer, filter number, optional parameter)
;
            public      filter
if          @bigmodel
filter      proc        far
else
filter      proc        near
endif
;
            push        bp
            mov         bp,sp               ;set up stack frame
            add         sp,AUTO
            push        ds                  ;save regs
            push        es
            mov         dx,FFUNC[bp]        ;calculate filter function address
            mov         cl,2
            shl         dx,cl               ;dx = function number index
            assume      ds:@code
            mov         ax, @code
            mov         ds, ax
            mov         bx, offset jmptab
            add         bx, dx
            mov         dx, [bx]
            mov         FUNC[bp], dx
            mov         dx, 2[bx]
            mov         FUNC+2[bp], dx
            assume      ds:nothing
            mov         di,BUFOFF[bp]       ;row buffer area es:[di]
            mov         ax,BUFSEG[bp]
            mov         es, ax
            mov         ax,SCNMEM           ;screen data area ds:[si]
            mov         ds,ax
            mov         si,0
            mov         word ptr ROW[bp],1  ;start at row 1, column 1
            mov         cx, 1
            call        ulbank
            push        di
            call        mrow                ;move the first 3 rows into buffer
            call        mrow
            call        mrow
            pop         di
lp1:        mov         word ptr COLUMN[bp],1
            push        di
            push        si
lp2:        call        dword ptr FUNC[bp]
            or          bx,bx               ;set value between 0 and 255
            jns         lt0
```

```
            mov     bl,0
            jmp     ldvd
lt0:        cmp     bx,255
            jl      ldvd
            mov     bl,255
ldvd:       mov     cx,COLUMN[bp]       ;calculate where to write pi el
            call    rloank              ;set appropriate bank
            mov     ax,ROW[bp]
            mov     ch,al               ;low addr  = low  column, high addr =
low row
            mov     si,cx
            mov     [si],bl             ;write pixel data
            inc     di                  ;bump row buffer pointer
            inc     word ptr COLUMN[bp]
            cmp     word ptr COLUMN[bp],511
            jnbe    temp1
            jmp     lp2                 ;do for column = 1 to 511
temp1:      pop     si
            pop     di
            inc     word ptr ROW[bp]    ;bump row count
            call    moverow
            mov     cx, ROW[bp]
            call    ulbank
            cmp     word ptr ROW[bp],510     ;do for row = 1 to 510
            jnbe    temp2
            jmp     lp1
temp2:      pop     es
            pop     ds
            mov     sp,bp
            pop     bp
            ret
filter      endp
;
;
moverow:
            push    si
            push    ds
            mov     ax, es
            mov     ds, ax
            mov     si, 512
            add     si, di
            mov     cx, 512
            cld
            rep     movsw               ;shift row buffer up one row
            pop     ds
            pop     si
            mov     cx,ROW[bp]
            inc     cx
            call    ulbank              ;set bank for next row
            cld
            call    mrow                ;read in the next row
            mov     di,BUFOFF[bp]       ;reset row buffer pointer
            mov     cx,ROW[bp]          ;reset bank for present row
            call    ulbank
```

```
        ret
;
mrow:
        mov     di,SCNBNK
        cld
        mov     cx,128              ;move left half row from screen to
row buffer
        rep     movsw
        sub     si,256              ;bump screen pointer start of right
bank
        in      al,dx               ;set bank to right half
        or      al,1
        out     dx,al
        mov     cx,128              ;move right half row from screen to
row buffer
        rep     movsw
        in      al,dx               ;set bank to left half
        and     al,2
        out     dx,al
        ret
;
ulbank:                             ;set upper or lower bank by row value
in cx
        mov     dx,SCNBNK ;ch = upper/lower bank number
        mov     al,ch
        shl     al,1
        out     dx,al
        ret
;
rlbank:                             ;set right or left bank by column
value in cx
        mov     dx,SCNBNK
        in      al,dx
        and     al,2
        or      al,ch               ;ch = right/left bank number
        out     dx,al
        ret
;
edge    proc    far
        mov     ah,0
        mov     al,es:D11[di]           ;D11 times 9
        mov     bx, ax
        mov     cl,3
        shl     ax,cl
        add     bx, ax
        mov     ah, 0                   ;for negadd
        negadd  es:D00[di]
        negadd  es:D01[di]
        negadd  es:D02[di]
        negadd  es:D10[di]
        negadd  es:D12[di]
        negadd  es:D20[di]
        negadd  es:D21[di]
        negadd  es:D22[di]
```

```
            ret
ecge .      endp
;
laplace     proc    far
            mov     bh,0
            mov     bl,es:D11[di]           ;D11 times 8
            mov     cl,3
            shl     bx,cl
            mov     ah, 0                   ;for negadd
            negadd  es:D00[di]
            negadd  es:D01[di]
            negadd  es:D02[di]
            negadd  es:D10[di]
            negadd  es:D12[di]
            negadd  es:D20[di]
            negadd  es:D21[di]
            negadd  es:D22[di]
;           mov     cl, 3
;           shl     bx, cl
            add     bx, 128
            ret
laplace     endp
;
sobel       proc    far
            mov     bh,0
            mov     bl,es:D01[di]
            shr     bx, 1
            accbx   es:D00[di]
            accbx   es:D02[di]
            mov     cx,bx
            mov     bh,0
            mov     bl,es:D21[di]
            shr     bx, 1
            accbx   es:D20[di]
            accbx   es:D22[di]
            sub     bx,cx
            abs     bx
            push    bx
            mov     bh,0
            mov     bl,es:D10[di]
            shr     bx, 1
            accbx   es:D00[di]
            accbx   es:D20[di]
            mov     cx,bx
            mov     bh,0
            mov     bl,es:D12[di]
            shr     bx, 1
            accbx   es:D02[di]
            accbx   es:D22[di]
            sub     bx,cx
            abs     bx
            pop     ax
            add     bx,ax
            ret
```

```
sobel   endp
;
roberts proc    far
        mov     bh,0
        mov     bl,es:D11[di]
        mov     ah, 0                           ;for negadd
        negadd  es:D22[di]
        abs     bx
        mov     cx,bx
        mov     bh,0
        mov     bl,es:D21[di]
        negadd  es:D12[di]
        abs     bx
        add     bx,cx
        ret
roberts endp
;
saltpep proc    far
        mov     bh,0
        mov     bl,es:D00[di]
        accbx   es:D01[di]
        accbx   es:D02[di]
        accbx   es:D10[di]
        accbx   es:D12[di]
        accbx   es:D20[di]
        accbx   es:D21[di]
        accbx   es:D22[di]
        mov     ah,0
        mov     al,es:D11[di]
        mov     cl,3
        shl     ax,cl
        sub     ax,bx
        abs     ax
        cmp     ax,OPT[bp]
        jg      spf1
        mov     bh,0
        mov     bl,es:D11[di]
        ret
spf1:   mov     cl,3
        shr     bx,cl
        ret
saltpep endp

;       table of addresses for filter functions
jmptab: dd      edge
        dd      laplace
        dd      sobel
        dd      roberts
        dd      saltpep
        include f:epilogue.h
        end
```

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